DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS
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BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 46

A STUDY OF THE ATTERBERG PLASTICITY METHOD

BY

CHARLES S. KINNISON, Assistant Physicist
Bureau of Standards

[ISSUED MAY 25, 1915]

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(Continued on third page of cover)

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A STUDY OF THE ATTERBERG PLASTICITY METHOD

By Charles S. Kinnison

CONTENTS

I. DESCRIPTION OF THE ATTERBERG METHOD

1. EXPLANATION OF TERMS AND METHODS OF PROCEDURE

A method of measuring plasticity is described by Albert Atterberg (International Reports on Pedology, 1911), which is based upon the varying physical behavior of clays with different water contents. According to this author, as we add water in increasing amounts to a clay powder, the clay first assumes a condition where it can be made to hold together by pressure, then the state where it possesses its best working qualities, passing into a sticky condition, and finally is as a thin, watery fluid with an excess of water. The various clays assume any one of these conditions within varying limits of water content. For instance, if a clay is possessed of good plasticity, there is a considerable range

in the water content within which it remains workable, while one in which plasticity is feeble permits only of a narrow range in its water content. If we determine the limits of the water content, according to Atterberg, at which the various clays pass from one condition to the other, we have a valuation of their relative plasticities.

Atterberg classifies the condition of a clay with varying amounts of water into five states, as follows: (1) The upper limit of fluidity or the point where the clay slip flows as water; (2) the lower limit of fluidity or flow, where two portions of the clay mass can be made to barely flow together, when placed in a shallow dish, which is sharply rapped with the hand; (3) the normal consistency, or sticky limit, being the condition in which the clay is most workable, is no longer sticky and will not adhere to metal; (4) the rolling limit, or the condition in which the clay can no longer be rolled into so-called threads between the hand and the surface on which it may rest (this is the lower limit of the workable condition); (5) the condition in which the damp clay will no longer hold together when subjected to pressure.

According to this classification, it is apparent that the workable stage is limited by the boundaries of condition (2) and condition (4); or, in other words, a clay is workable between the point where it will barely flow (where this point is determined by the method mentioned above), and the point at which it can no longer be rolled into threads. It is Atterberg's contention that the wider this range the more plastic is the clay.

2. FIXING OF FLOW LIMIT AND ROLLING LIMIT

It is clear that the establishment or fixing of these points is arbitrary. The method adopted by Atterberg is as follows:

(*a*) The Flow Limit or the Upper Boundary of the Plastic Condition.—About 5 grams of the clay powder, of approximately 120 mesh, are put into a small porcelain evaporating dish and made into a paste by the addition of distilled water. By means of a polished nickel spatula the mass is shaped into a smooth layer, a trifle less than 1 cm (0.39 inch) in thickness. The clay is then divided into two portions by cutting a triangular-shaped

channel (as shown by sketch (Fig. 1), through the mass, the lower edges being separated a trifle).

The dish is then repeatedly and sharply rapped against the heel of the hand in order to bring about the flowing together of the separated portions. The flow limit has been reached when the two portions of the clay can barely be made to meet at the bottom, as shown. If the paste is too thick or too thin, water or clay is added until the proper consistency has been attained.

The water content of the clay mass in this condition is then carefully determined by drying to constant weight and the value expressed in terms of percentage of the dry weight of the clay.

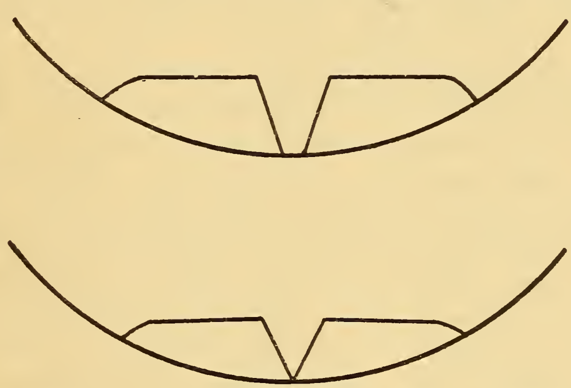

Fig. 1.—*Determination of flow-limit*

(*b*) The Lower Plasticity Limit or the So-called Rolling Limit.—Clay in the stiff plastic condition is rolled between the hands and any plane smooth surface covered with paper until slender cylindrical threads form. These "threads" may break up into smaller lengths, but this is of no significance. Dry clay powder is added to the plastic mass and thoroughly incorporated in it, and the rolling operation repeated. The desired consistency has been attained when the clay can no longer be fashioned into threads by this method, but crumbles instead. This condition can be recognized rather sharply, and no difficulty is experienced in checking the results. The water is determined for this consistency and expressed in terms of percentage of the dry weight of the clay. This figure subtracted from the one determined by

(*a*) gives a figure which is called the "plasticity number," and the higher its value the more plastic is the clay. The physical significance of such a number is that it expresses the range in water content which a clay may have and still be considered plastic.

II. REVIEW OF ATTERBERG'S WORK

1. EFFECT OF ADDITION OF SAND

In this connection a revised adaptation of a method originated by Bischof was used by Atterberg, in which the clay is mixed with varying amounts of sand of different fineness (0.2 to 0.06 mm) and the effect of such additions on the plasticity studied. Atterberg's method consisted in adding fine sand to the clay powder in the ratio of clay to sand as 1 : 0.5, 1 : 1, and 1 : 2. The lower flow limit, the condition of normal consistency, and the rolling limit or lower plasticity limit were then determined in these three mixtures. If the mass at the flow limit could not be rolled into threads, it was considered as nonplastic. Those clays which could be mixed with two parts of sand without losing their plasticity were considered as belonging to the first class, or of highest plasticity; those which could carry only an equal part of sand were put into the second class, while those which lost their plasticity upon an addition of half their weight of or practically no sand were classed third. The results of this experiment showed that the shape of the sand grains was of much more influence than was their size.

2. RELATION BETWEEN VARIOUS CONSISTENCIES

The above experiments of Atterberg on 19 different clays showed that if a clay having a lower water content at the condition of normal consistency than at the flow limit be mixed with much sand the relative position of the condition of normal consistency is always raised in reference to the flow limit, and in some cases rises above it, which shows that the condition of normal consistency can not be considered as the upper plasticity limit. In those cases, however, where the water content of the normal consistency lies above that of the flow limit the latter must be considered as the upper limit of plasticity.

III. SUMMARY OF ATTERBERG'S RESULTS

The accompanying diagram (Fig. 2), illustrating type curves, summarizes the relations between the flow limit, the condition of normal consistency, and the rolling limit for the clays of the different plasticities.

The diagram shows that these three conditions stand in the following relations to each other: The flow limit and the rolling

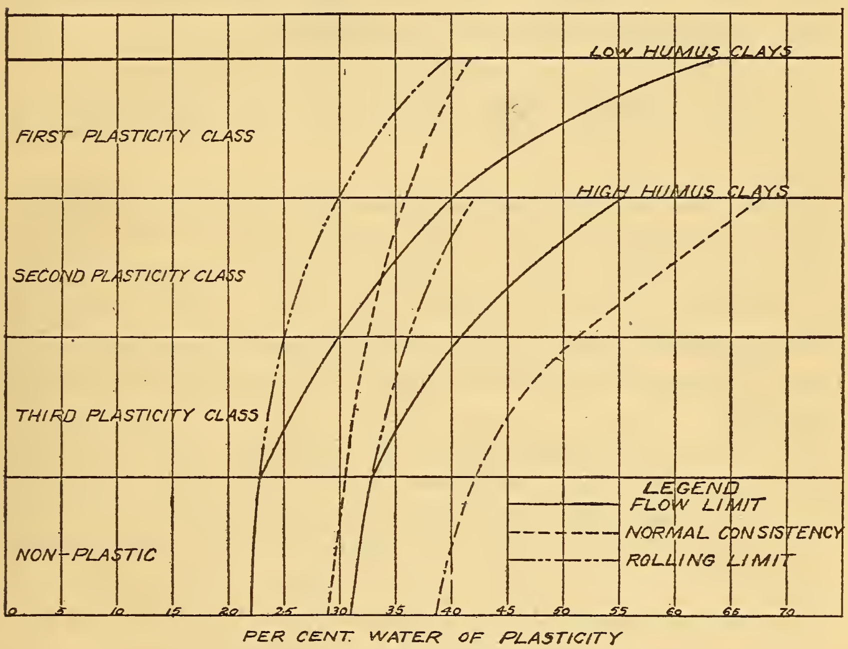

FIG. 2.—*Diagram showing Atterberg's classification*

limit coincide in the case of the loams, which Atterberg classifies as nonplastic, but in the case of the clays they separate more and more as the plasticity increases. These two limits must therefore be considered as bounding the consistencies within which the clay is plastic.

The curve showing the condition of normal consistency however, follows a decidedly different course. In the case of the loams, or "nonplastics," and the clays rich in humus this limit lies much higher than that of the flow limit.

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In the clays low in or free from humus the relative position of the flow limit is higher. In the case of highest plasticity the condition or normal consistency always takes a place below that of the flow limit and approaches more and more the rolling limit, practically coinciding in the clays of highest plasticity.

The condition of normal consistency or the point where the clay is no longer sticky can not, therefore, be considered the upper limit of plasticity. The flow limit rather must form the upper boundary line of the plastic condition.

It is interesting to note that the water content at the normal consistency and at the flow limit approach each other in the less plastic clays, coinciding in the second class, from which point they diverge.

Since, however, the condition of normal consistency in the case of the clays of the first class falls between the flow limit and the rolling limit, two types of plasticity must be recognized, viz, the condition of sticky plasticity and that of the nonsticky. Atterberg claims that the failure to appreciate this distinction has been the cause of failure of so many of the methods determining plasticity.

Although the condition of normal consistency lies outside the field of the true plastic condition, it still lies within the plastic area in the case of the most plastic clays, in which cases it forms the boundary line between the conditions of sticky and nonsticky plasticity.

The water content at the condition of normal consistency in the clays of the first plasticity class is always lower than at the flow limit, while in the clays belonging to the third class and in the loams the water content at this consistency is always higher than at the flow limit. In the clays mixed with sand, normal consistency was always higher than or in the neighborhood of the flow limit.

TABLE 1

Clay class and number	Flow limit	Roll limit	Plasticity number	Humus content
I. Plasticity class:	*Per cent*	*Per cent*		*Per cent*
1	67	40	27	0.9
2	57	30	27	.9
3	51	26	25	1.7
4	44	23	21	.0
5	42	25	17	.9
II. Plasticity class:				
6	52	37	15	4.2
7	33	19	14	.5
8	42	30	12	5.9
9	31	21	10	3.2
10	32	25	7	.7
III. Plasticity class:				
11	28	21	7	.0
12	30	24	6	.7
13	64	58	6	10.8
14	58	52	6	High.
15	33	28	5	4.7
16	22	18	4	1.9

The figures compiled in Table 1 were used by Atterberg in drawing the diagram of Fig. 2. There are two sets of curves shown—those to the left, applying to the clays low in humus, and those to the right, applying to the clays high in humus. The ordinate is arbitrarily divided into four parts, representing the four classes of plasticity, while the abscissa represents the water content of the clay. Therefore, the length of the abscissa, between any two analogous points on the curves representing the rolling limit and flow limit, respectively, expresses the value of the plasticity number of that clay.

The curves as drawn indicate that the plasticity number increases progressively with the water content. That is, if a clay has a plasticity number of 10, the respective limits of the water content must be higher than those of the clay whose plasticity number is, say, 6. His own results do not bear this out, however. Thus, clay No. 4, having a plasticity number of 21, contains 23 per cent water at the rolling limit, while No. 5, with a plasticity number of 17, has 25 per cent water at the rolling limit. Both belong to the low-humus class also, and therefore belong to the same set of curves. Clays Nos. 7 and 10, both low in humus, furnish a similar example, and also clays 11, 12, 13, and 14, the

latter two being both high in humus. His curves, therefore, do not exactly represent the facts.

Atterberg says that the humus content is of marked influence on a clay's properties, stating that high humus can be responsible for high water contents at the various limits. The diagram of Fig. 2 has been plotted on this basis, the curves representing the clays rich in humus having higher water content than the curves of the low-humus clays.

From the above table it is observed, however, that two clays may have the same plasticity numbers without having the same water content, and yet both contain the same amount of humus, as witness clays Nos. 1 and 2 and also Nos. 13 and 14, both of the latter being of high humus content. Thus, it is evident from Atterberg's own work that where two clays have equal plasticity numbers with widely different water contents, it does not follow that the clay having the higher water content must also contain the most humus, as Atterberg claims. This fact is also evident from the results of the present work. Clay No. 14, a china clay, has practically the same plasticity number as clay No. 1, a shale. It is certainly true that the china clay contains no humus, and it is very probable that the shale does; yet the former contains 25.5 per cent more water at the flow limit than does the shale, as shown by the figures of 68.0 per cent and 42.5 per cent, respectively.

It would appear, therefore, that the generalizations expressed by the curves of Fig. 2 are too broad and are based on results which are much too meager. We are furthermore not justified in terming all organic matter humus, after subtracting the carbonates, as Atterberg has done.

IV. DESCRIPTION OF PLASTICITY METHODS USED IN THE PRESENT WORK

The Atterberg method, while perhaps not so well known in America, is being used to some extent in Germany for classifying the clays according to their plasticity. The method is practically as simple a one as could be devised, and if it represents facts it is well that we should become familiar with it.

To compare it with some of the present methods for measuring plasticity, 20 different clays were selected, their plasticity meas-

ured by Atterberg's method, their water of plasticity and volume shrinkage determined, as well as the amount of water which the dry powders would absorb when allowed to stand over a dilute sulphuric-acid solution, a method recommended by Keppeler. It is not to be expected that the clays would be classified in the same order by all three of these methods, but from the combined results of these tests we should be able to classify them rather accurately according to their relative plasticities, inasmuch as they are all directly related in some manner to this property of the clay. The clays used are compiled in the following table:

TABLE 2

Clay	Remarks	Clay	Remarks
1. Bedford shale	Very good working properties.	11. Tennessee ball clay, No. 3.	Very plastic; rather sticky.
2. G. R. Murray shale	Do.	12. Great Beam ball clay	Do.
3. McKeehan shale	Excellent working properties.	13. Whitaway ball clay	Do.
4. Metropolitan shale	Good working properties.	14. M. W. M. china clay	Fairly plastic; sticky.
5. Deckman-Duty shale	Fair working properties.	15. M. G. R. No. 2 china clay.	Do.
6. Galesburg shale	Good working properties.	16. Aultman No. 3 fire clay	Good working properties.
7. Kittanning fire clay	Do.	17. Georgia kaolin	Very plastic; sticky.
8. Union Furnace fire clay	Do.	18. North Carolina kaolin	Slightly plastic; sticky.
9. Chicago Retort & Fire Clay Co. clay.	Do.	19. Texas white clay, No. 340	Extremely plastic; very sticky.
10. M. & M. ball clay, No. 1	Very plastic; rather sticky.	20. Florida kaolin	Good plasticity; sticky.

1. ATTERBERG'S METHOD

For carrying on Atterberg's test the clays were thoroughly mixed and screened through an 80-mesh sieve and the method recommended by him was followed as accurately as possible. However, instead of using a shallow evaporating dish for determining the flow limit a flat vitrified porcelain disk was substituted, because when the former was used there seemed to be a tendency for the clay mass to slide instead of flow. This trouble was eliminated by the use of the flat disk. Atterberg does not specify the width which shall separate the two portions of clay, but in our case this distance was made about one-eighth inch. Nothing is

definitely stated concerning the vigor or number of blows which shall be given to bring about the flow, and of course the more vigorous and frequent are these blows the lower will be the flow limit. In our work the disk was sharply rapped 25 times against the heel of the hand, care being taken to make the impacts of as near the same intensity as possible. Of course these could not be made exactly equal in each case and this difference constitutes one source of error. We would suggest that a mechanical device of some sort be used for this determination, such as a vibrator. It seems, furthermore, that these impacts should be made against some rigid object instead of the hand.

Table 3 shows the results. All the results contained in this table are expressed in terms of the dry volume or the dry weight. This method classifies the clays as shown in column A of Table 4. The figures expressed in the various columns indicate the plasticities of the different clays, position No. 1 being held to be the most plastic and No. 20 to be the least plastic clay.

TABLE 3

Clay number	Volume shrinkage	Water of plasticity	Water absorbed	Atterberg's method		
				Water content at flow limit	Water content at rolling limit	Plasticity number
	Per cent	Per cent	Per cent	Per cent	Per cent	
1	27.7	27.7	5.21	42.5	22.4	20.1
2	31.4	27.6	3.34	39.7	23.0	16.7
3	18.6	21.4	2.20	32.6	19.6	13.0
4	17.7	26.0	3.33	40.7	25.3	15.4
5	18.3	25.0	4.27	38.1	26.2	11.9
6	20.8	26.7	2.43	37.0	25.0	12.0
7	23.2	20.6	4.79	32.1	17.5	14.6
8	26.4	26.3	3.20	37.0	21.4	15.6
9	19.6	18.1	4.90	26.8	15.0	11.8
10	48.2	49.3	10.50	120.9	37.2	83.7
11	54.5	52.5	10.30	100.0	43.7	56.3
12	35.2	45.3	7.84	70.0	42.5	27.5
13	35.0	43.8	7.22	78.3	35.7	42.6
14	27.1	44.1	2.19	68.0	48.6	19.4
15	25.0	43.3	2.51	64.3	46.4	17.9
16	27.4	25.0	4.79	34.4	18.8	15.6
17	23.7	26.2	4.71	64.8	35.5	29.3
18	23.1	34.2	4.75	56.5	41.8	14.7
19	81.8	64.8	20.90	306.0	54.1	251.9
20	32.1	45.2	5.68	83.5	42.5	41.0

2. VOLUME SHRINKAGE AND WATER OF PLASTICITY

In determining the volume shrinkage each clay was worked to its best consistency, which corresponds to the normal consistency in Atterberg's work. This condition was merely judged by feel. The clays were then put into a damp closet and allowed to stand overnight, when they were removed and small cylindrical pieces of about 50-cc contents made for determining the volume shrinkage, the volume measurements being made in kerosene. The water of plasticity was also determined at the same time.

These pieces were dried by a method similar to that recommended by Kerr and Montgomery, viz, air-drying for about five days, then drying to constant weight at 75°, and finally taking to complete dryness at 110° C. The pieces were then dipped in paraffin and their volume determined. Table 3 shows these results. The rating of the clays by these methods is shown in columns B and C of Table 4.

3. WATER ABSORPTION

For determining the water-absorption properties, the specimens were subjected to the vapor of a 10 per cent H_2SO_4 solution. About 2 grams of each clay was accurately weighed, as a powder passing through an 80-mesh screen, in small tin capsules, after having been taken to dryness at 110°. These were then put into a vacuum desiccator containing the acid solution and allowed to stand. Weighings were then made at the end of 7 and 14 days, and then about every 2 days until practically constant weight was attained. It can be readily seen that changes in temperatures will affect the weight of the clays, inasmuch as the vapor pressure of the solution changes with the temperature. In case of a fall in temperature there results a loss in weight due, of course, to the evaporation of the water from the samples. This is only noticeable when the clays practically reach their maximum weight, because, as this point is approached, their rate of increase in weight is very slow. These results are compiled in Table 3. The classification on this basis is found in column D of Table 4.

V. DISCUSSION OF RESULTS

In studying the results compiled in Table 4 it is noticeable that there is fairly close agreement in the classification by the different methods with the exception of the arrangement based on water absorption. As is to be expected, the classification according to the Atterberg method and that based on the percentage of water of plasticity agree more closely than any other two of the methods used.

TABLE 4

Position numbers

Clay number	A Atterberg	B H_2O plasticity	C Shrinkage	D H_2O absorption	B×C Position by product of B and C in order of magnitude	A×B Position by product of A and B in order of magnitude	A×B×D Position by product of A×B×D in order of magnitude	Average of A, B, and C	Points off average by shrinkage	Points off average by H_2O plasticity	Points off average by Atterberg
1	8	12	8	7	11	10	10	9.3	1.3	2.7	1.3
2	11	11	7	14	9	12	11	9.7	2.7	1.3	1.3
3	17	18	18	19	19	18	19	17.7	.3	.3	.7
4	14	15	20	15	17	14	15	16.3	3.7	1.3	2.3
5	19	16	19	12	18	17	18	18.0	1.0	2.0	1.0
6	18	13	16	18	15	15	17	15.7	.3	2.7	2.3
7	16	19	14	16	16	16	16	16.3	2.3	2.7	.3
8	12	14	11	13	12	13	14	12.0	1.0	2.0	.0
9	20	20	17	....	20	20	20	19.0	2.0	1.0	1.0
10	2	2	3	2	3	2	2	2.3	.7	.3	.3
11	3	3	2	3	2	3	3	2.7	.7	.3	.3
12	7	4	4	4	4	6	6	5.0	1.0	1.0	2.0
13	4	7	5	5	5	4	4	5.3	.3	1.7	1.3
14	9	6	10	....	7	7	7	8.3	1.7	2.3	.7
15	10	8	12	....	8	8	8	10.0	2.0	2.0	.0
16	13	17	9	9	13	19	13	13.0	4.0	4.0	.0
17	6	10	15	11	14	9	9	10.3	4.7	.3	3.7
18	15	9	13	10	10	11	12	12.3	.7	3.3	2.7
19	1	1	1	1	1	1	1	1.0	.0	.0	.0
20	5	5	6	6	6	5	5	5.3	.7	.3	.3
Total									31.1	31.5	21.5

The disagreement in the different evaluations is such, however, as to make it evident that no one of these methods used alone will suffice. Each of them produced results which contradict the facts as we observe them from everyday experience with the clays. Thus, by Atterberg's method, North Carolina kaolin

(No. 18) and Kittanning fire clay (No. 7) are rated as of practically equal plasticity, whereas all agree that the latter clay should rank decidedly ahead of the former, based on experience with both clays. Similarly, Georgia kaolin (No. 17) is ranked ahead of Great Beam ball clay (No. 12). Both are considered as very plastic, but based on popular conceptions the ball clay is more so.

These misrepresentations seem to be due to the fact that Atterberg's factor, which is obtained simply from the difference between two numbers, does not take into account a sufficient number of factors. It does not locate the clays in their respective classes. That is, two clays may have practically the same plasticity numbers and yet their water contents be widely different. North Carolina and the Kittanning fire clay are rated as being of practically equal plasticity, as indicated by the plasticity factors of 14.7 and 14.6. The former has a water content of 56.5 per cent at the flow limit and the latter only 32.1 per cent; at the rolling limit the kaolin contains 41.8 per cent, while the fire clay but 17.5 per cent. The Bedford shale (No. 1) and the M. W. M. china clay (No. 14) furnish another example of this sort. (See Table 3.)

The classification based upon the gain in weight of the clays when subjected to an atmosphere of aqueous vapor is quite at variance in its valuation of the clays compared to the other schemes tried. Thus clays Nos. 9, 14, and 15 are given positions which are decidedly different from the valuation as indicated by the other methods. Clay No. 9, from the Chicago Retort & Clay Co., is generally classified as the least plastic clay of the 20, except by this method, which seems to give it a valuation more nearly representing our everyday conception of it. Clays 14 and 15 are both china clays, whose working properties are only fair, yet they are classed among the more plastic ones, except by this method, which seems to classify them in a more representative position.

Experimental difficulties, such as recognizing the condition of equilibrium, make the results of Keppeler's test somewhat untrustworthy. For the results to represent the true maximum gain in weight the specimens should be maintained at a constant temperature.

We may say that plasticity varies as the amount of water necessary to develop plasticity and as the shrinkage. Therefore, it may vary in some way as the product of these two factors. The column B and C in Table 4 rates the clays according to the magnitude of this product. We can not safely say that this classification is a correct one, based on this joint factor, because we do not definitely know that plasticity is affected to the same degree by a change of each of these factors; that is, it may be possible that plasticity is much more closely allied with shrinkage than it is upon the amount of water necessary to develop plasticity. The order as given in column C and B is a correct one, based on the relation of plasticity to water content and shrinkage, provided both are of equal importance or influence on the plasticity. It does, however, for mathematical reasons alone, give a more nearly accurate rating of the clays than either column C or B alone. We are unable to say *a priori* that such a procedure will give the true facts of the case, and we will only know that it is correct when it produces results which coincide with the facts as observed from the practical use of the clays. It checks practical observations fairly well and is therefore not extremely at variance with the facts.

The foregoing remarks also apply to the results contained in column A and B, where the clays are rated according to the magnitude of the product of Atterberg's factor times the water of plasticity.

To arrive at conclusions relative to the respective values of the different methods used, the "average position number" was determined, as shown in column "Average of A, B, and C," of Table 4, and it was then seen which of the methods gave a classification nearest the average. The average is the mean of the values given in columns A, B, and C, and does not include those obtained by Keppeler's method or the values obtained from the product of any of the factors. It would obviously be unfair, for mathematical reasons, to include in this mean figure the values obtained from those columns marked $A \times B$ or $B \times C$, and then rate the merits of the different methods on a basis of the extent of their variance from the average. Atterberg's method gives results nearest the average of the classifications based on A, B, and C.

VI. MODIFIED ADAPTATION OF THE ATTERBERG FACTOR

As was mentioned above, the Atterberg factor does not take into consideration a sufficient number of conditions. It assumes that clays behave very much the same when in a plastic condition,

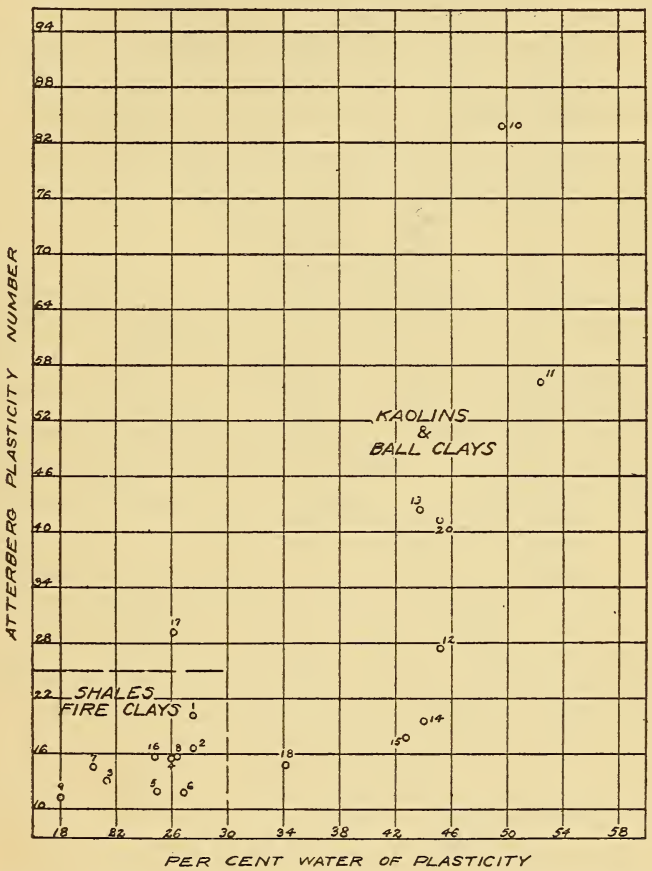

FIG. 3.—*Diagram showing relation between Atterberg plasticity number and total water content*

and does not consider the amount of water required to develop plasticity. It would seem better to coordinate Atterberg's factor with the water of plasticity.

For practical working purposes, then, we can evaluate clays by a graphical method illustrated in Fig. 3, wherein those varieties

which are workable in a stiff-clay machine are separated from the sticky secondary varieties, which are difficult to work, requiring quite a large amount of water to develop plasticity and which have but feeble characteristics in that respect, being sticky instead of plastic, and often characterized by poor bonding power.

In this diagram we have used the Atterberg plasticity number as the ordinate and the percentage of water of plasticity as the abscissa. It brings out the fact that Atterberg's factor can not be satisfactorily used to evaluate clays in regard to their plasticities unless they are all of one type; that is, it will not classify accurately a large number of clays of various types.

VII. SUMMARY

From the above paragraphs it is seen that Atterberg's factor gives a rating nearest the mean, and is therefore to be preferred to either of the ratings based on shrinkage or water of plasticity. However, this factor when used alone has but little significance. With it, there should be coordinated the water of plasticity, such a procedure having been adopted in Fig. 3. This scheme gives promise of separating the nonsticky and safe working clays from the sticky varieties difficult to work.

A large number, say 100, of well-selected representative clays of all kinds when studied in this manner should establish areas or limits within which clays would be readily workable.

From the 20 clays studied in this work we can say that those clays are safely workable in the unmixed state whose water of plasticity does not exceed 30 per cent and whose plasticity number is not more than 25. The most reliable rating of these clays in regard to their plasticity is found in column $A \times B \times D$ of Table 4. This classification is necessarily close to the average of A, B, and C and is, furthermore, more nearly correct than the mean.

WASHINGTON, December 30, 1914.

(Continued from second page of cover)

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